

University of Technology Sydney
Faculty of Engineering and Information Technology

**An Investigation of
Free Surface Hydraulic Structures Using
Large Eddy Simulation and
Computational Fluid Dynamics**

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A dissertation submitted in fulfilment of the
requirements for the degree of Doctor of Philosophy.

13 April 2011

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CERTIFICATE OF ORIGINALITY

I certify that the work in this dissertation has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the dissertation has been written by me. Any help that I have received in my research work and the preparation of the dissertation itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the dissertation.

A handwritten signature in black ink, appearing to read "P. Brag". The signature is fluid and cursive, with the first letter "P" being large and prominent.

Signature of Candidate

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Contents

Table of Contents

CERTIFICATE OF ORIGINALITY	III
ACKNOWLEDGEMENTS.....	V
CONTENTS	VII
TABLE OF CONTENTS	VII
LIST OF FIGURES	XV
LIST OF TABLES	XXVII
LIST OF APPENDICES.....	XXIX
NOMENCLATURE.....	XXXI
<i>English Symbols</i>	<i>xxxi</i>
<i>Greek Symbols.....</i>	<i>xxxiii</i>
<i>Mathematical Operators.....</i>	<i>xxxiv</i>
<i>Subscripts</i>	<i>xxxv</i>
<i>Superscripts</i>	<i>xxxv</i>
<i>Other Operators and Variables</i>	<i>xxxv</i>
<i>Non-dimensional Groups.....</i>	<i>xxxvi</i>
<i>Acronyms</i>	<i>xxxvi</i>
ABSTRACT	XXXIX
1. INTRODUCTION	1
1.1. SCALES OF FLUID DYNAMICS	1
1.2. POLICY FRAMEWORK	3
1.3. THE SCALES AND TYPES OF CIVIL ENGINEERING SIMULATIONS	5
1.4. SEWER OVERFLOWS AND STORMWATER DISCHARGE DEVICES	6
<i>1.4.1. Characteristics of Flows to Be Simulated.....</i>	<i>6</i>
<i>1.4.2. Common Overflow Management Devices Installed</i>	<i>8</i>
<i>1.4.3. Sewer and Combined Sewer Overflow Design and Research</i>	<i>11</i>
1.5. FLOW FEATURES TO BE SIMULATED.....	16
1.6. OUTLINE OF THE RESEARCH PROGRAM.....	17

1.7. SELECTION CRITERIA FOR THE VALIDATION STUDIES	18
1.8. SELECTION OF THE SINGLE PHASE VALIDATION CONFIGURATION	19
1.9. SELECTION OF THE TWO-PHASE VALIDATION STUDIES.....	20
1.10. MAPPING OF THE RESEARCH PROGRAM TO THIS DOCUMENT	22
2. MATHEMATICAL MODELS OF SINGLE PHASE FLUIDS	25
2.1. INTRODUCTION	25
2.2. CONSERVATION EQUATIONS	25
2.2.1. <i>Conservation of Mass</i>	25
2.2.2. <i>Conservation of Momentum</i>	26
2.3. INTRODUCTION TO TURBULENCE	28
2.4. DIRECT NUMERICAL SIMULATION	34
2.5. LARGE EDDY SIMULATION	35
2.5.1. <i>Filtering the Navier-Stokes Equations</i>	35
2.5.2. <i>LES Models</i>	37
2.6. IS AVERAGING A SOLUTION TO THE RESOLUTION REQUIREMENTS OF DNS AND LES?	38
2.6.1. <i>Averaging the Navier-Stokes Equations</i>	38
2.6.2. <i>The Closure Problem</i>	42
2.7. TURBULENCE MODELS FOR THE REYNOLDS AVERAGED FORMULATION	44
2.8. HYBRID TURBULENCE MODELS: DETACHED EDDY SIMULATION	46
2.9. ILES: THE ALTERNATIVE USED IN THIS RESEARCH	46
3. THE FINITE VOLUME METHOD	49
3.1. INTRODUCTION AND CONVENTIONS.....	49
3.2. INTEGRATION OF THE GENERAL CONSERVATION EQUATION	51
3.3. DISCRETISATION OF THE GENERAL CONSERVATION EQUATION	52
3.3.1. <i>The Surface Flux Integral Terms</i>	52
3.3.2. <i>The Source and Volume Integral Terms</i>	54
3.3.3. <i>The Unsteady Term and Time Integrals</i>	55
3.4. FINITE DIFFERENCE SCHEMES	56
3.4.1. <i>Spatial and Temporal Schemes in CFD-ACE+</i>	56

3.4.2. <i>The Unsteady Term</i>	57
3.4.3. <i>Convection Term</i>	59
3.5. THE GENERAL FINITE VOLUME EQUATION	62
3.6. BOUNDARY CONDITIONS	62
3.6.1. <i>Application of Boundary Conditions</i>	62
3.6.2. <i>Fixed Value Boundaries</i>	63
3.6.3. <i>Wall Functions</i>	64
3.7. COUPLING OF THE VELOCITY AND PRESSURE FIELDS	65
3.7.1. <i>Continuity and Mass Conservation</i>	65
3.7.2. <i>SIMPLEC for Transient Problems</i>	66
3.8. FLUID PROPERTIES	68
4. NUMERICAL SIMULATION OF FREE SURFACES	69
4.1. MODEL REQUIREMENTS	69
4.2. NUMERICAL MODELS OF FREE SURFACES	69
4.3. THE VOLUME OF FLUID MODEL	73
4.4. THE PLIC METHOD FOR SURFACE RECONSTRUCTION.....	74
4.4.1. <i>Overview of the PLIC Method</i>	74
4.4.2. <i>Computation of Truncation Volumes</i>	76
4.5. SURFACE TENSION AND CONTACT ANGLES.....	78
4.5.1. <i>Surface Tension</i>	78
4.5.2. <i>Wall Contact Angle</i>	78
5. SINGLE PHASE VALIDATION: CONFIGURATION AND FLOW FIELD.....	81
5.1. INTRODUCTION	81
5.2. PRELIMINARY TWO-DIMENSIONAL INVESTIGATIONS.....	82
5.3. CONFIGURATION OF THE THREE-DIMENSIONAL SIMULATIONS	88
5.3.1. <i>Geometry and Computational Mesh</i>	88
5.3.2. <i>Boundary and Initial Conditions</i>	95
5.3.3. <i>Solver Parameters</i>	95
5.4. CONVERGENCE OF THE SOLVER DURING THE SIMULATIONS	96
5.5. OBSERVATIONS OF THE GLOBAL FLOW FIELD FROM THE SPANWISE PERIODIC MESHES	96

5.5.1. <i>Three Dimensional Structures</i>	96
5.5.2. <i>Velocity Magnitude Distribution along the $z=0$ Plane</i>	101
5.5.3. <i>Vorticity and Velocity Magnitude Cut Planes</i>	104
5.6. SPANWISE VELOCITY CORRELATIONS	107
5.6.1. <i>Description and Validation of the Sampling Technique Used in the Present Work</i>	107
5.6.2. <i>Correlation Analysis of the Data from the Present Work</i>	110
5.7. REVIEW OF THE FLOW VISUALISATIONS	116
6. SINGLE PHASE VALIDATION: POINT AND INTEGRAL DATA	117
6.1. INTRODUCTION	117
6.2. GRID CONVERGENCE	117
6.2.1. <i>Methodology</i>	117
6.2.2. <i>Velocity Components as a Function of Time</i>	118
6.2.3. <i>Statistical Characteristics of the Velocity Traces</i>	119
6.2.4. <i>Outcome of the Grid Convergence Study</i>	122
6.3. SPATIAL DOMAIN ANALYSIS OF TIME AVERAGED DATA	123
6.3.1. <i>Motivation for Time Averaging</i>	123
6.3.2. <i>Method to Compute the Online Averages</i>	124
6.3.3. <i>Methods to Test the Quality of the Average Statistics</i>	125
6.3.4. <i>Quality of the Averages from the Present Work</i>	127
6.3.5. <i>Comparison with Averaged Experimental Data</i>	134
6.3.6. <i>Comparison with Averaged Numerical Data</i>	136
6.4. SPECTRAL ANALYSIS OF TURBULENCE STATISTICS	150
6.4.1. <i>Introduction</i>	150
6.4.2. <i>Specific Method of Computation</i>	151
6.4.3. <i>Power Spectra and Dominant Frequencies</i>	151
6.4.4. <i>Decay Slope Estimation</i>	154
6.4.5. <i>Turbulent Length Scales</i>	158
6.5. SINGLE PARAMETER VALIDATION: INTEGRAL QUANTITIES	160
6.5.1. <i>Quantities Considered</i>	160

6.5.2. Mean C_D and C_L	160
6.5.3. Root Mean Squared C_D and C_L	162
6.5.4. Recirculation Length	165
6.5.5. Base Pressure Coefficient	166
6.5.6. Discussion of the Single Parameter Results	167
6.6. WALL TIME.....	167
6.7. DISCUSSION OF THE SINGLE PHASE VALIDATION STUDIES	169
7. FLOWS WITH A FREE SURFACE	173
7.1. INTRODUCTION	173
7.2. THE CYLINDER CENTRED INERTIAL FRAME OF REFERENCE	177
7.3. CYLINDER CENTRED BOUNDARY CONDITIONS	179
7.4. CYLINDER CENTRED VOLUME CONDITIONS	180
7.5. NON-DIMENSIONAL NUMBERS	181
8. TWO-PHASE PRELIMINARY STUDIES	183
8.1. INTRODUCTION	183
8.2. AN INQUIRY INTO THE INFLUENCE OF A HYDROSTATIC PRESSURE VARIATION AT THE INLET AND OUTLET BOUNDARIES	184
8.2.1. Motivation for this Study.....	184
8.2.2. Geometric Design, Grid Layout and Solver Configuration.....	185
8.2.3. Convergence of the Solver During the Simulations	187
8.2.4. Observations and Discussions from the Hydrostatic Tests.....	187
8.3. A STUDY OF THE GRID AND GEOMETRIC CONFIGURATIONS	196
8.3.1. Motivation for these Studies.....	196
8.3.2. Geometric Design and Grid Layout: Common Parameters	197
8.3.3. Geometric Design and Grid Layout: Test Specific Modifications	200
8.3.4. Solver Configuration	202
8.3.5. Point Probe Locations.....	203
8.3.6. Convergence of the Solver During the \mathfrak{F} Simulations.....	204
8.3.7. Observations from the Parametric Tests of \mathfrak{F}	204
8.3.8. Convergence of the Solver During the \mathcal{L} Tests.....	210

8.3.9. Observations from the Parametric Tests of \mathcal{L}	211
8.4. RECOMMENDATIONS FOR THE DEVELOPMENT OF THE THREE-DIMENSIONAL MODELS FROM THE TWO-PHASE PRELIMINARY STUDIES.....	220
9. THREE-DIMENSIONAL, TWO-PHASE SIMULATIONS: CONFIGURATION AND THE SIMULATED FREE SURFACE SHAPE	223
9.1. INTRODUCTION	223
9.2. CONFIGURATION OF THE SIMULATIONS	224
9.2.1. General Geometric Configuration	224
9.2.2. Configuration of the Computational Meshes	226
9.2.3. Time Step and Solver Configuration.....	233
9.3. CONVERGENCE AND STABILITY OF THE NUMERICAL SOLVER	235
9.4. VISUAL EXAMINATION OF THE SIMULATED FREE SURFACES.....	235
9.4.1. Case 1: Full Depth, $Re_d = 27 \times 10^3$	235
9.4.2. Case 2: Full Depth, $Re_d = 54 \times 10^3$	248
9.4.3. Case 3: Partial Depth, $Re_d = 54 \times 10^3$	250
10. THREE-DIMENSIONAL, TWO-PHASE SIMULATIONS: POINT, TIME DOMAIN AND SPECTRAL RESULTS	253
10.1. WAVE SHAPE PARAMETERS	253
10.1.1. Introduction	253
10.1.2. Bow Wave Height – D_1	253
10.1.3. Cavity Depth – L_0	257
10.1.4. Rooster Tail Height – D_3	259
10.1.5. Rooster Tail Length – L_3	260
10.2. SPECTRAL VALIDATION	262
10.3. COMPUTATIONAL RUN TIME TESTS.....	265
11. THREE-DIMENSIONAL, TWO-PHASE SIMULATIONS: DRAG FORCES EXPERIENCED BY THE CYLINDER.....	267
11.1. INTRODUCTION.....	267
11.2. FORCES ON THE CYLINDERS	268
11.3. DRAG DUE TO THE PRESENCE OF THE FREE SURFACE.....	271

11.4. PRESSURE EFFECTS DUE TO THE PRESENCE OF A FREE SURFACE	275
11.5. ALTERNATIVE WAVE DRAG VALUES.....	280
12. CONCLUSION	283
13. BIBLIOGRAPHY.....	283

List of Figures

FIGURE 1-1 – RELATIVE SCALES OF FLUID MECHANICS AND DYNAMICS RESEARCH. POINTS ABOVE THE NUMBER LINE REPRESENT PUBLISHED MODEL SCALES WITH POINTS BELOW THE NUMBER LINE REPRESENTATIVE OF IDENTIFIABLE PHYSICAL OBJECTS FOR COMPARISON OF SIZES.....	2
FIGURE 1-2 – PARTICLE SIZE DISTRIBUTION OF SOLIDS RECOVERED FROM STORMWATER RUNOFF FROM ROAD CATCHMENTS, EXTRACTED FROM A META-STUDY BY WALKER ET AL (1999).	6
FIGURE 1-3 – PHOTOGRAPH OF THE FULL SUMP OF A CONTINUOUS DEFLECTION DEVICE PRIOR TO CLEANING (ROCLA, 2009).....	7
FIGURE 1-4 – SCHEMATIC REPRESENTATION, WITH INDICATIVE PHOTOGRAPHS, OF A THREE STAGE OFFLINE STORMWATER TREATMENT SYSTEM AND ASSOCIATED CREEK REHABILITATION.	9
FIGURE 1-5 – TRASH RACK GPT, WITH TRAPPED LEAF LITTER AND LOW FLOW OUTLET.	9
FIGURE 1-6 – A PHOTOGRAPH OF SEWER OVERFLOW STRUCTURE IN SYDNEY THAT IS DESIGNED TO DISCHARGE EFFLUENT DIRECTLY INTO A CONCRETE LINED STORMWATER CHANNEL NEAR PUNCHBOWL (AVIS, 2001).....	10
FIGURE 1-7 – PHOTOGRAPH OF A SCALE MODEL OF A SINGLE SIDE WEIR SEWER OVERFLOW CHAMBER (BEECHAM, 1991). THE OVERFLOW OUTLET IS THE WOODEN CHUTE SHOWN IN THE FOREGROUND WHILE THE LOW FLOW OUTLET PIPE IS LOCATED ON THE BOTTOM RIGHT OF THE IMAGE.	12
FIGURE 1-8 – SKETCH OF THE CENTRE PLANE OF THE SEWER STORAGE CHAMBER USED BY STOVIN AND SAUL (1996), DIMENSIONS IN METRES.....	13
FIGURE 1-9 – DOMINANT FLOW REGIME IDENTIFIED BY STOVIN AND SAUL (1996).....	14
FIGURE 1-10 – EXAMPLE IMAGES FROM THE THREE CAMERA LOCATIONS: (A) THE CAMERA BEHIND THE CYLINDER SHOWING A PERSPECTIVE OF THE WAKE; (B) THE CAMERA SIDE-ON AND ABOVE THE FREE SURFACE, AND; (C) THE CAMERA SIDE-ON AND PARALLEL WITH THE FREE SURFACE, AN IMAGE SUITABLE FOR PHOTOGRAMMETRY.....	22
FIGURE 2-1 – PLOT OF EQUATIONS (2.6), (2.7) AND (2.8) WITH CONSTANTS OF PROPORTIONALITY OF UNITY AND A CHARACTERISTIC LENGTH OF 0.05M FOR WATER AT 20°C.....	28
FIGURE 2-2 – SCHEMATIC ILLUSTRATION OF THE VORTEX-ON-VORTEX CONCEPTUALISATION OF TURBULENCE.....	29
FIGURE 2-3 – IDEALISED TURBULENT ENERGY SPECTRUM AS A FUNCTION OF WAVE NUMBER ON LOG-LOG SCALES, ADAPTED FROM WILCOX (1998) AND NEZU AND NAKAGAWA (1993).....	31
FIGURE 3-1 – DEFINITION SKETCH FOR A FINITE VOLUME CELL USING STANDARD CARDINAL DIRECTIONS TO IDENTIFY CELL FACES.	50
FIGURE 3-2 – SKETCH OF THE NODES AND FACES USED IN A ONE-DIMENSIONAL CONTROL VOLUME, ADAPTED FROM VERSTEEG AND MALALASEKERA (1996).....	53

FIGURE 3-3 – REGULAR TWO-DIMENSIONAL GRID FOR THE EXPLANATION OF THE BARTH AND JESPERSEN GRADIENT ESTIMATION TECHNIQUE (BARTH AND JESPERSEN, 1989).....	60
FIGURE 3-4 – WALL ADJACENT COMPUTATIONAL CELL EXAMPLE SKETCH	63
FIGURE 3-5 – ASSUMED LAMINAR VELOCITY DISTRIBUTION AT A WALL, REPRODUCED FROM VERSTEEG AND MALALASEKERA (1996)	64
FIGURE 3-6 – FLOW DIAGRAM OF THE TRANSIENT SIMPLEC ALGORITHM.....	67
FIGURE 4-1 – SCHEMATIC OF A SELECTION OF CELLS THAT ARE CUT BY AN INTERFACE THAT WOULD IN TURN NEED TO BE RE-MESHED WITH AN INTERFACE TRACKING SCHEME (BAI ET AL., 2009).....	71
FIGURE 4-2 – INCLINED FREE SURFACE SHOWING SMEARING OF THE INTERFACE DUE TO THE INTERFACE CAPTURING METHOD USED IN VOF.	72
FIGURE 4-3 – RECONSTRUCTION OF A CIRCULAR ARC USING THE PLIC APPROXIMATION, NUMBERS ARE CELL VOLUME FRACTIONS (KOTHE ET AL., 1996).....	75
FIGURE 4-4 – TWO-DIMENSIONAL CELL FOR A SAMPLE TRUNCATION VOLUME COMPUTATION.	77
FIGURE 4-5 – SKETCH OF CONTACT ANGLE AND WALL VECTORS (ESI CFD INC., 2007A).	79
FIGURE 5-1 – SKETCH OF THE SQUARE CYLINDER IN A DUCT CONFIGURATION WITH THE PRINCIPLE COORDINATE AXES AND NAMING SCHEME IDENTIFIED.	81
FIGURE 5-2 – DIAGRAM OF THE TWO-DIMENSIONAL GEOMETRY USED AS THE BASIS FOR THE PRELIMINARY TESTS.....	83
FIGURE 5-3 – SKETCH OF THE DEFINITION OF THE WALL NORMAL CELL LENGTH.	83
FIGURE 5-4 – IMAGE OF THE VELOCITY MAGNITUDE SHOWING A HIGH-SPEED EVENT THAT WAS SUBSEQUENTLY EJECTED OUT OF THE WAKE TOWARDS THE TOP WALL.	84
FIGURE 5-5 – VELOCITY MAGNITUDE VISUALISATION OF A VON KÁRMÁN VORTEX STREET BEHIND A SQUARE CYLINDER, REPRODUCED FROM JOHANSEN, WU AND SHYY (2004).....	85
FIGURE 5-6 – COMPARISON OF THE RESOLVED FLOW FEATURES IN THE $\mathfrak{F}=5\text{MM}$ (A) AND THE $\mathfrak{F}=50\text{MM}$ (B) SIMULATIONS WITH THE FLOW VISUALISED BY THE VELOCITY MAGNITUDE AND INSTANTANEOUS STREAMLINES TO INDICATE THE RECIRCULATION ZONES.	85
FIGURE 5-7 – DRAG COEFFICIENTS AS A FUNCTION OF TIME FOR $\mathfrak{F}=5\text{MM}$ AND $\mathfrak{F}=50\text{MM}$	86
FIGURE 5-8 – PROBABILITY DISTRIBUTION FUNCTION OF THE LIFT COEFFICIENTS COMPUTED ACROSS THE SIMULATION TIME INTERVAL OF $10 \leq t \leq 100$ s FROM THE TEN \mathfrak{L} SIMULATIONS.	87
FIGURE 5-9 – PROBABILITY DISTRIBUTION FUNCTIONS OF THE LIFT COEFFICIENTS COMPUTED ACROSS THE SIMULATION TIME INTERVAL $10 \leq t \leq 100$ s FROM THE SEVEN \mathfrak{F} SIMULATIONS.....	87
FIGURE 5-10 – COMPARATIVE DIAGRAM OF THE GEOMETRY OF THE SPANWISE PERIODIC AND WATER TUNNEL CONFIGURATIONS SHOWING THE CYLINDER CENTRED COORDINATE ORIGIN.	89

FIGURE 5-11 – GRID AND DOMAIN LAYOUT FOR THE RIGHT SQUARE CYLINDER MODELS.	90
FIGURE 5-12 – TOTAL CELL COUNT FOR THE FOUR SQUARE CYLINDER MODELS AND THEIR SIZE RELATIVE TO THE LOW RESOLUTION MESH.	93
FIGURE 5-13 – LATERAL CELL SIZE AS A FUNCTION OF Y COORDINATE FOR THE MESHES.	94
FIGURE 5-14 – STREAMWISE CELL SIZE AS A FUNCTION OF X COORDINATE FOR THE MESHES.	94
FIGURE 5-15 – CUMULATIVE DISTRIBUTION FUNCTIONS OF N_{ITER} FOR THE FOUR SIMULATIONS.	96
FIGURE 5-16 – FLOW VISUALISATION OF ISOSURFACES OF VORTICITY MAGNITUDE AT $ \Omega =25\text{s}^{-1}$ SURFACES COLOURED BY VELOCITY MAGNITUDE FROM THE HIGH-RESOLUTION MESH AT A SIMULATION TIME OF $T=34.0\text{s}$	97
FIGURE 5-17 – THREE PERSPECTIVE VIEWS OF THE SIMULATION TIME OF $T=8.6\text{s}$ FROM THE HIGH- RESOLUTION MESH WITH TWO RIBS AND TWO ROLLS IDENTIFIED AND ANNOTATED.	98
FIGURE 5-18 – FLOW VISUALISATION OF ISOSURFACES OF VORTICITY MAGNITUDE AT $ \Omega =25\text{s}^{-1}$ COLOURED BY VELOCITY MAGNITUDE, FROM THE HIGH-RESOLUTION MODEL AT A SIMULATION TIME OF $T=35.0\text{s}$	100
FIGURE 5-19 – Q CRITERION VORTEX STRUCTURES ADAPTED FROM SONG AND PARK (2009).	100
FIGURE 5-20 – FLOW VISUALISATION ON THE $Z=0$ PLANE FROM THE HIGH-RESOLUTION SIMULATION, TIME $T=34.4\text{s}$	101
FIGURE 5-21 – FLOW VISUALISATION OF THE VELOCITY MAGNITUDE ACROSS A $Z=0$ PLANE FROM THE HIGH- RESOLUTION MODEL AT A SIMULATION TIME OF 35.0s	102
FIGURE 5-22 – FLOW VISUALISATION ON THE CENTRE PLANE OF THE FULLY DEVELOPED FLOW COMPUTED BY HOFFMAN (2005).....	102
FIGURE 5-23 – IDEALISED 3D WAKE TOPOLOGY FROM THE HORIZONTAL PERTURBATION MODEL (MEIBURG AND LASHERAS, 1988), REPRODUCED FROM DOBRE AND HANGAN (2004).	103
FIGURE 5-24 – CUT PLANE AT $Z=0$ FROM THE HIGH-RESOLUTION MODEL AT $T=35.0$ SHOWING VELOCITY MAGNITUDE IN GREY SCALE AND VORTICITY MAGNITUDE CONTOURS IN COLOUR AND A THREE- DIMENSIONAL VIEW WITH AN ISOSURFACE OF $\Omega=25\text{s}^{-1}$	104
FIGURE 5-25 – CUT PLANE AT $Y=0$ FROM THE HIGH-RESOLUTION MODEL AT $T=34.6$ SHOWING VELOCITY MAGNITUDE IN GREY SCALE AND VORTICITY MAGNITUDE CONTOURS IN COLOUR (B) AND A THREE- DIMENSIONAL VIEW WITH AN ISOSURFACE OF $ \Omega =25\text{s}^{-1}$ (A).	105
FIGURE 5-26 – FLOW VISUALISATION OF THE VORTICITY MAGNITUDE (COLOUR CONTOURS) AND THE VELOCITY MAGNITUDE (GREYSKALE) ON THE $Y=0$ PLANE FROM THE WATER TUNNEL SIMULATION, TIME $T=41\text{s}$ AND THE ISOSURFACES AT $ \Omega =25\text{s}^{-1}$	106
FIGURE 5-27 – AUTOCORRELATION FUNCTION FOR A POINT LOCATED AT $(0.250, 0, 0)\text{m}$ SHOWING THE AFFECT OF A CHANGE OF SAMPLE RATES FOR THE U -VELOCITY.	108

FIGURE 5-28 – AUTOCORRELATION FUNCTION FOR A POINT LOCATED AT (0.250, 0, 0)M SHOWING THE AFFECT OF A CHANGE OF SAMPLE RATES FOR THE V -VELOCITY	109
FIGURE 5-29 – AUTOCORRELATION FUNCTION FOR A POINT LOCATED AT (0.250, 0, 0)M SHOWING THE AFFECT OF A CHANGE OF SAMPLE RATES FOR THE W -VELOCITY	109
FIGURE 5-30 – SCHEMATIC OF THE SPANWISE DISTRIBUTION OF SAMPLING POINTS USED IN THE CORRELATION ANALYSIS	110
FIGURE 5-31 – LOCATION OF THE POINT PROBES CHOSEN FOR THE CORRELATION ANALYSIS WITH THE COMPUTATIONAL BOUNDARIES AND AN INDICATIVE LOCATION OF THE WAKE BOUNDARY	111
FIGURE 5-32 – R_{LM} CORRELATION COEFFICIENTS FOR BOTH THE WATER TUNNEL AND THE HR SPANWISE PERIODIC SIMULATIONS AS A FUNCTION OF SEPARATION OVER THE LINE UC1	112
FIGURE 5-33 – R_{LM} CORRELATION COEFFICIENTS FOR BOTH THE WATER TUNNEL AND THE HR SPANWISE PERIODIC SIMULATIONS AS A FUNCTION OF SEPARATION OVER THE LINE SC1	112
FIGURE 5-34 – R_{LM} CORRELATION COEFFICIENTS FOR BOTH THE WATER TUNNEL AND THE HR SPANWISE PERIODIC SIMULATIONS AS A FUNCTION OF SEPARATION OVER THE LINE WC1	113
FIGURE 5-35 – R_{LM} CORRELATION COEFFICIENTS FOR BOTH THE WATER TUNNEL AND THE HR SPANWISE PERIODIC SIMULATIONS AS A FUNCTION OF SEPARATION OVER THE LINE WC2	113
FIGURE 5-36 – R_{LM} CORRELATION COEFFICIENTS FOR BOTH THE WATER TUNNEL AND THE HR SPANWISE PERIODIC SIMULATIONS AS A FUNCTION OF SEPARATION OVER THE LINE WC3	114
FIGURE 5-37 – R_{LM} CORRELATION COEFFICIENTS FOR BOTH THE WATER TUNNEL AND THE HR SPANWISE PERIODIC SIMULATIONS AS A FUNCTION OF SEPARATION OVER THE LINE WC4	115
FIGURE 6-1 – LOCATION OF THE POINT PROBE IN RELATION TO THE SQUARE CYLINDER AND THE APPROXIMATE BOUNDARY OF THE WAKE REGION.	118
FIGURE 6-2 – U VELOCITY AS A FUNCTION OF TIME FOR THE POINT PROBE AT (0.78,0,0)M.	119
FIGURE 6-3 – DISTRIBUTION FUNCTION OF THE U -VELOCITIES FROM THE FOUR SIMULATIONS.	120
FIGURE 6-4 – DISTRIBUTION FUNCTION OF THE V -VELOCITIES FROM THE FOUR SIMULATIONS.	120
FIGURE 6-5 – DISTRIBUTION FUNCTION OF THE W -VELOCITIES FROM THE FOUR SIMULATIONS.	121
FIGURE 6-6 – MINIMUM, MAXIMUM, MEAN AND THE STANDARD DEVIATION FOR THE PRINCIPLE VELOCITIES FROM THE POINT PROBE AT (0.078, 0, 0)M, SEE FIGURE 6-1.	121
FIGURE 6-7 – MODE, MEDIAN, SKEWNESS AND KURTOSIS FOR THE PRINCIPLE VELOCITIES FROM THE POINT PROBE AT (0.078, 0, 0)M.	122
FIGURE 6-8 – DIAGRAM OF THE DEVELOPMENT OF THE AVERAGES AND THE THREE PHASES OF ONLINE AVERAGING.	124

FIGURE 6-9 – EXAMPLE OF THE DEVELOPMENT OF THE AVERAGES AND FLUCTUATING STATISTICS AS A FUNCTION OF TIME.	126
FIGURE 6-10 – DEFINITION SKETCH OF THE LINE AND THE PERPENDICULAR DISTANCE.	127
FIGURE 6-11 – VISUALISATION OF THE TIME AVERAGED U -VELOCITY ON THE $z=0$ PLANE FOR THE LR, MR, HR AND WT SIMULATIONS, SUBPLOT (A) – (D) RESPECTIVELY.	128
FIGURE 6-12 – MAGNIFICATION OF THE NEAR CYLINDER REGIONS OF FIGURE 6-11.	129
FIGURE 6-13 – SKETCH OF THE LOCATION OF POINT PROBES FOUR AND EIGHT RELATIVE TO THE DOMAIN BOUNDARIES AND THE INDICATIVE WAKE EXTENT.	129
FIGURE 6-14 – THE DEVELOPMENT OF THE AVERAGES AND MEAN SQUARED FLUCTUATIONS AS A FUNCTION OF TIME FOR THE LR SIMULATION AT POINT PROBE FOUR.	130
FIGURE 6-15 – THE DEVELOPMENT OF THE AVERAGES AND MEAN SQUARED FLUCTUATIONS AS A FUNCTION OF TIME FOR THE HR SIMULATION AT POINT PROBE EIGHT.	131
FIGURE 6-16 – SCATTER PLOT OF THE UPPER AND LOWER POINTS FOR THE TIME AVERAGED U - AND V -VELOCITIES FROM THE MEDIUM-RESOLUTION SIMULATION.	132
FIGURE 6-17 – HISTOGRAM OF \mathfrak{D} FOR THE U - AND V -VELOCITIES FROM THE FOUR SIMULATIONS.	133
FIGURE 6-18 – POINT-BY-POINT COMPARISON OF THE HIGH RESOLUTION SIMULATION DATA FROM THE PRESENT WORK WITH THE EXPERIMENTAL DATA OF LYN AND RODI (1994).	134
FIGURE 6-19 – POINT-BY-POINT COMPARISON OF THE WATER TUNNEL SIMULATION DATA FROM THE PRESENT WORK WITH THE EXPERIMENTAL DATA OF LYN AND RODI (1994).	135
FIGURE 6-20 – HISTOGRAM OF \mathfrak{D} AS A FUNCTION OF THE PERCENTAGE ERROR DEFINED IN EQUATION (6.9).	136
FIGURE 6-21 – LOCATION OF THE FOUR COMPARISON LINES WITHIN THE $z = 0$ PLANE USED AT THE DLES2 CONFERENCE DESCRIBED BY VOKE (1996).	137
FIGURE 6-22 – U -VELOCITY PLOT ALONG THE $y=0, z=0$ LINE OF THE PRESENT RESULTS COMPARED WITH RESULTS FROM THE DLES2 WORKSHOP (VOKE, 1996) AND THE EXPERIMENTAL DATA OF LYN AND RODI (1994).	138
FIGURE 6-23 – MAGNIFICATION OF THE U -VELOCITIES IN NEAR CYLINDER REGION OF FIGURE 6-22.	139
FIGURE 6-24 – CENTRELINE PLOT OF THE TIME AVERAGE OF THE $v'v'$ FLUCTUATIONS.	140
FIGURE 6-25 – ZOOM OF THE NEAR CYLINDER RESULTS PLOTTED IN FIGURE 6-24.	141
FIGURE 6-26 – CENTRELINE PLOT OF THE TIME AVERAGE OF THE $u'u'$ FLUCTUATIONS.	142
FIGURE 6-27 – CENTRELINE PLOT OF THE TIME AVERAGE OF THE $w'w'$ FLUCTUATIONS.	143

FIGURE 6-28 – TIME AVERAGE U -VELOCITIES FROM THE PRESENT SIMULATIONS, THE EXPERIMENTAL DATA OF LYN AND RODI (1994) AND THE COMPILED RESULTS OF VOKE (1996) ALONG CONSTANT x LINES IN THE $z = 0$ PLANE.....	145
FIGURE 6-29 – TIME AVERAGE $U'U'$ FLUCTUATIONS FROM THE PRESENT SIMULATIONS, THE EXPERIMENTAL DATA OF LYN AND RODI (1994) AND THE COMPILED RESULTS OF VOKE (1996) ALONG CONSTANT x LINES IN THE $z = 0$ PLANE.	146
FIGURE 6-30 – TIME AVERAGE $V'V'$ FLUCTUATIONS FROM THE PRESENT SIMULATIONS, THE EXPERIMENTAL DATA OF LYN AND RODI (1994) AND THE COMPILED RESULTS OF VOKE (1996) ALONG CONSTANT x LINES IN THE $z = 0$ PLANE.	148
FIGURE 6-31 – TIME AVERAGE $U'V'$ FLUCTUATIONS FROM THE PRESENT SIMULATIONS, THE EXPERIMENTAL DATA OF LYN AND RODI (1994) AND THE COMPILED RESULTS OF VOKE (1996) ALONG CONSTANT x LINES IN THE $z = 0$ PLANE.	149
FIGURE 6-32 – POWER SPECTRAL DENSITY OF THE V -VELOCITY FOR A POINT ON THE WAKE CENTRELINE AT $x=0.078$ M FROM THE HIGH-RESOLUTION SIMULATION.	152
FIGURE 6-33 – COMPARISON OF STROUHAL NUMBERS FROM PUBLISHED DATA AND THE FOUR SIMULATIONS OF PRESENT WORK.	153
FIGURE 6-34 – INDICATIVE SLOPE OF THE PSD TRACES IN THE POWER-LAW DECAY REGIONS FOR EIGHT POINTS LOCATED IN THE WAKE ALONG THE $y = 0, z = 0$ LINE.....	157
FIGURE 6-35 – KOLMOGOROV LENGTHS COMPUTED ALONG THE WAKE CENTRE LINE.....	159
FIGURE 6-36 – COMPARISON OF MEAN DRAG COEFFICIENTS FROM PUBLISHED DATA AND THE FOUR SIMULATIONS OF PRESENT WORK.	161
FIGURE 6-37 – COMPARISON OF MEAN LIFT COEFFICIENTS FROM PUBLISHED DATA AND THE FOUR SIMULATIONS OF PRESENT WORK.	162
FIGURE 6-38 – COMPARISON OF ROOT MEAN SQUARED DRAG COEFFICIENTS FROM PUBLISHED DATA AND THE FOUR SIMULATIONS OF PRESENT WORK.	163
FIGURE 6-39 – COMPARISON OF ROOT MEAN SQUARED LIFT COEFFICIENTS FROM PUBLISHED DATA AND THE FOUR SIMULATIONS OF PRESENT WORK.	164
FIGURE 6-40 – COMPARISON OF RECIRCULATION LENGTHS.	165
FIGURE 6-41 – COMPARISON OF COEFFICIENTS OF BASE PRESSURE FROM PUBLISHED DATA AND THE FOUR SIMULATIONS OF PRESENT WORK.	166
FIGURE 6-42 – COMPARISON OF MODEL RUN SPEEDS FOR DIFFERENT LES SUBGRID MODELS AND AN INDICATIVE K-EPSILON RANS MODEL.	169
FIGURE 7-1 – ALL 900 DRAG COEFFICIENTS MEASURED BY HAY (1947) PLOTTED AS A FUNCTION OF FROUDE NUMBER RELATIVE TO THE DIAMETER.	176

FIGURE 7-2 – DIAGRAM OF A SUB-SECTION OF THE DAVID TAYLOR MODEL BASIN WITH THE SURFACE PIERCING CIRCULAR CYLINDER AND THE FREE SURFACE SHOWN.....	177
FIGURE 7-3 – DIAGRAM OF THE CONFIGURATION OF THE CYLINDER CENTRED REFERENCE FRAME.	178
FIGURE 7-4 – PLOT OF THE NORMALISED INLET VELOCITY AS A FUNCTION OF TIME.....	180
FIGURE 7-5 – PLOT OF THE NORMALISED ACCELERATION AS A FUNCTION OF TIME.	181
FIGURE 8-1 – SKETCH OF THE TWO-DIMENSIONAL CHANNEL MODEL AND THE EDGE AND BOUNDARY LAYOUT USED FOR TESTING THE HYDROSTATIC PRESSURE ASSUMPTION.	185
FIGURE 8-2 – CUMULATIVE PROBABILITY DISTRIBUTION OF N_{ITER} FOR BOTH THE NO AIR AND WITH AIR SIMULATIONS.	187
FIGURE 8-3 – SNAPSHOT OF THE FLOW FIELD AT TIME, $t = 0$, FOR BOTH SIMULATIONS WITH THE DOMAIN COLOURED BY THE FLUID VELOCITY MAGNITUDE AND THE FREE SURFACE A BLUE LINE.	188
FIGURE 8-4 – SNAPSHOT OF THE PRESSURE DISTRIBUTION AT TIME, $t = 0$, FOR THE NO AIR (A) AND THE WITH AIR (B) SIMULATIONS.	188
FIGURE 8-5 – CONTOUR PLOT OF THE PRESSURE DIFFERENTIAL DEFINED IN EQUATION (8.3).	189
FIGURE 8-6 – VISUALISATION OF THE VELOCITY MAGNITUDE AND THE LOCATION OF THE FREE SURFACE AT A $t = 0.1$ S FOR THE NO AIR (A) AND THE WITH AIR (B) SIMULATIONS.	190
FIGURE 8-7 – VELOCITY VECTORS COLOURED BY THEIR MAGNITUDE AT THE AIR AND WATER OUTLETS AT TIME $t = 0.1$ S FOR THE NO AIR AND THE WITH AIR CASES, (A) AND (B) RESPECTIVELY.....	191
FIGURE 8-8 – INDICATIVE PRESSURE DISTRIBUTION AT $t = 0.1$ S FOR THE TWO SIMULATIONS.	191
FIGURE 8-9 – CONTOUR PLOTS OF THE PRESSURE DIFFERENTIAL DEFINED IN EQUATION (8.4).	192
FIGURE 8-10 – SNAPSHOT OF THE FLOW FIELD AT $t=5.1$ S FOR THE NO AIR (A) AND THE WITH AIR (B) SIMULATIONS WITH THE DOMAIN COLOURED BY THE VELOCITY MAGNITUDE AND THE FREE SURFACE BY A SOLID BLUE LINE.	193
FIGURE 8-11 – VELOCITY VECTORS ALONG CONSTANT X LINES FOR THE NO AIR SIMULATION – SUBPLOTS (A) AND (C) – AND THE WITH AIR MODEL – SUBPLOTS (B) AND (D).	194
FIGURE 8-12 – SKETCH OF PRESSURE IMBALANCES CAUSING UNPHYSICAL BOUNDARY FLOWS.	195
FIGURE 8-13 – SKETCH OF THE TWO-DIMENSIONAL PLANE USED IN THE GEOMETRY TESTS WITH THE LENGTH TO THE OUTLET BOUNDARY, \mathcal{L} , AND THE WALL NORMAL CELL SIZE, \mathfrak{F} , SHOWN.	196
FIGURE 8-14 – DIMENSIONAL SKETCH (IN MILLIMETRES) AND GRID LAYOUT FOR THE TWO-DIMENSIONAL MESH USED IN TESTING THE SIZE OF THE INNER CYLINDER CELL.	198
FIGURE 8-15 – MAGNIFICATION OF THE CENTRAL STRUCTURED O-TYPE DOMAINS ADJACENT TO THE CYLINDER AND THE TRANSITIONAL UNSTRUCTURED DOMAIN.	199
FIGURE 8-16 – CELL COUNT AND NUMBER OF NODES ALONG EDGE JN FOR THE SIX \mathfrak{F} MESHES.	200

FIGURE 8-17 – PLOT OF THE RADIAL CELL SIZE AS A FUNCTION OF THE RADIAL DISTANCE FOR SIX TESTS OF DIFFERENT WALL NORMAL CELL SIZES.	201
FIGURE 8-18 – CELL COUNT AND NUMBER OF NODES ALONG EDGE EF FOR THE 11 SIMULATIONS OF \mathfrak{L}	202
FIGURE 8-19 – PLOT OF THE POINT PROBE LOCATIONS.	203
FIGURE 8-20 – CUMULATIVE PROBABILITY DISTRIBUTIONS OF N_{ITER} FOR THE SIX \mathfrak{F} SIMULATIONS.	204
FIGURE 8-21 – C_D AND C_L AS A FUNCTION OF TIME FROM THE $\mathfrak{F} = 5\text{MM}$ AND $\mathfrak{F} = 1\text{MM}$ SIMULATIONS, (A) AND (B) RESPECTIVELY.	205
FIGURE 8-22 – VELOCITY MAGNITUDE OF THE FLOW FIELD FROM THE $\mathfrak{F} = 5\text{MM}$ SIMULATION.	206
FIGURE 8-23 – VELOCITY MAGNITUDE OF THE IMAGE FROM THE $\mathfrak{F} = 0.50\text{MM}$ SIMULATION.	206
FIGURE 8-24 – C_D AND C_L AS A FUNCTION OF TIME FROM THE $\mathfrak{F} = 0.50\text{MM}$ SIMULATION.	207
FIGURE 8-25 – VELOCITY MAGNITUDE OF THE FLOW FIELD FROM THE $\mathfrak{F} = 0.05\text{MM}$ SIMULATION.	207
FIGURE 8-26 – C_D AND C_L AS A FUNCTION OF TIME FROM THE $\mathfrak{F} = 0.25\text{MM}$ (A), $\mathfrak{F} = 0.15\text{MM}$ (B) AND $\mathfrak{F} = 0.05\text{MM}$ (C) SIMULATIONS.	208
FIGURE 8-27 – ZOOM OF THE VELOCITY MAGNITUDE IN THE REGION CLOSE TO THE CYLINDER FOR (A) $\mathfrak{F}=5.00\text{MM}$ AND (B) $\mathfrak{F}=0.05\text{MM}$ SIMULATIONS, RESPECTIVELY.	208
FIGURE 8-28 – AVERAGE C_D AND RMS C_L AS A FUNCTION OF \mathfrak{F}	209
FIGURE 8-29 – CUMULATIVE PROBABILITY DISTRIBUTIONS OF N_{ITER} FOR THE 11 \mathfrak{L} SIMULATIONS.	211
FIGURE 8-30 – THE VON KÁRMÁN VORTEX STREET VISUALISED WITH THE VELOCITY MAGNITUDE FOR THE $\mathfrak{L} = 400\text{MM}$ (A), $\mathfrak{L} = 1199$ (B) AND $\mathfrak{L} = 2998$ (C) SIMULATIONS.	212
FIGURE 8-31 – DIFFERENCE IN THE VELOCITY FIELDS BETWEEN THE $\mathfrak{L} = 2998$ MM AND THE $\mathfrak{L} = 1199$ MM SIMULATIONS; AND THE $\mathfrak{L} = 2998$ MM AND THE $\mathfrak{L} = 400$ MM SIMULATIONS, (A) AND (B) RESPECTIVELY.	213
FIGURE 8-32 – PLOT OF THE FOUR OF THE LENGTH TEST U -VELOCITIES AS A FUNCTION OF TIME FOR THE SEVEN POINT PROBES.	214
FIGURE 8-33 – PLOT OF THE FOUR OF THE LENGTH TEST V -VELOCITIES AS A FUNCTION OF TIME FOR THE SEVEN POINT PROBES.	215
FIGURE 8-34 – PLOT OF U -VELOCITIES (CIRCLE SYMBOLS AND SOLID LINES) AND THE RMS V -VELOCITIES AS A FUNCTION OF \mathfrak{L} FOR POINT PROBE LOCATED AT $X=28\text{MM}$	216
FIGURE 8-35 – PLOT OF U -VELOCITIES (CIRCLE SYMBOLS AND SOLID LINES) AND THE RMS V -VELOCITIES AS A FUNCTION OF \mathfrak{L} FOR THE POINT PROBES LOCATED AT $X = 200\text{MM}$	216
FIGURE 8-36 – \mathfrak{U}_{pr} FOR THE MEAN U -VELOCITY AS A FUNCTION OF THE DISTANCE OF THE POINT PROBES FROM THE OUTLET BOUNDARIES.	217

FIGURE 8-37 – U_{Pr} FOR THE RMS v -VELOCITY AS A FUNCTION OF THE DISTANCE OF THE POINT PROBES FROM THE OUTLET BOUNDARIES.	218
FIGURE 8-38 – C_D AND C_L AS A FUNCTION OF TIME FROM THE $\mathcal{L} = 685\text{MM}$ SIMULATION.	219
FIGURE 8-39 – PLOT OF THE MEAN DRAG AND THE RMS LIFT COEFFICIENTS AS A FUNCTION \mathcal{L}	220
FIGURE 9-1 – SKETCH OF THE CYLINDER CENTRED DOMAIN, REPEATED FROM FIGURE 7-3.	223
FIGURE 9-2 – SKETCH OF THE GEOMETRY, BOUNDARY CONDITIONS AND COORDINATE ORIGIN USED IN THE CIRCULAR CYLINDER INVESTIGATIONS, ALL DIMENSIONS ARE IN MILLIMETRES.	225
FIGURE 9-3 – GEOMETRY AND EDGE SKETCH FOR FULL DEPTH CONFIGURATION WITH ALL DIMENSIONS IN MILLIMETRES.	228
FIGURE 9-4 – GEOMETRY AND EDGE SKETCH FOR THE CUT OFF CYLINDER CONFIGURATION WITH ALL DIMENSIONS IN MILLIMETRES.	230
FIGURE 9-5 – PLOTS OF THE CELL SIZE ALONG LINES THAT CONTAIN THE POINT (0,0,0) AND ARE PARALLEL TO THE x -, y -, AND z -AXES (A), (B) AND (C) RESPECTIVELY. DUE TO THE MIRROR-SYMMETRY AROUND THE $z=0$ PLANE, ONLY THE POSITIVE z -AXIS IS SHOWN IN (C).	232
FIGURE 9-6 – VIEW OF A y -PLANE TAKEN FROM THE MEDIUM RESOLUTION MODEL WITH THE DASHED, PURPLE LINES SHOWING THE FORCED ORTHOGONAL EDGES.	233
FIGURE 9-7 – CUMULATIVE PROBABILITY DISTRIBUTIONS OF N_{ITER} FOR THE FOUR FREE SURFACE PIERCING SIMULATIONS.	235
FIGURE 9-8 – MEDIUM RESOLUTION GRID, LOW SPEED OBLIQUE COMPARISON WITH EXPERIMENTAL PHOTOGRAPHS OF THE FREE SURFACE IN THE NEAR WAKE OF THE CYLINDER.	236
FIGURE 9-9 – MEDIUM RESOLUTION GRID, LOW SPEED SIDE VIEW COMPARISON WITH EXPERIMENTAL PHOTOGRAPHS OF THE FREE SURFACE IN THE NEAR WAKE OF THE CYLINDER.	237
FIGURE 9-10 – SHAPE OF THE INSTANTANEOUS FREE SURFACE FROM YU ET AL (2008).	238
FIGURE 9-11 – SKETCH OF THE STRUCTURE OF A SHIP WAKE REPRODUCED FROM ESA ('SHIP WAKES,' 2009).	239
FIGURE 9-12 – CONTOUR PLOT OF THE TIME-AVERAGED Y_{FS} (IN METRES) FROM THE PRESENT WORK WITH ANNOTATIONS HIGHLIGHTING PARTICULAR FEATURES.	241
FIGURE 9-13 – CONTOUR PLOT COMPARISON OF THE TIME-AVERAGED Y_{FS} FROM THE PRESENT WORK AND THE TOW TANK RESULTS OF INOUE ET AL (1993).	242
FIGURE 9-14 – CONTOUR PLOT COMPARISON OF THE OF THE TIME-AVERAGED Y_{FS} FROM THE PRESENT WORK AND THE TOW TANK SIMULATION OF YU ET AL (2008).	243
FIGURE 9-15 – CONTOUR PLOT COMPARISON OF THE TIME-AVERAGED Y_{FS} FROM THE PRESENT WORK AND THE TOW TANK RESULTS OF KAWAMURA ET AL (2002).	244

FIGURE 9-16 – Y_{FS} AS A FUNCTION OF Z FOR $X = 0.035$ M WITH THE ERROR BARS FROM THE PRESENT WORK INDICATIVE OF THE SPREAD RATHER THAN A MEASUREMENT ERROR.....	245
FIGURE 9-17 – PLOT OF THE HORIZONTAL LOCATION OF THE VERTICAL TRAVERSE LINES USED BY INOUE ET AL (1993) TO MEASURE THE VELOCITY RELATIVE TO THE ENTIRE COMPUTATIONAL DOMAIN OF THE PRESENT WORK (A) AND A MAGNIFICATION OF THE CYLINDER REGION (B).	246
FIGURE 9-18 – AVERAGE VELOCITY AS A FUNCTION OF Y_{FS} FOR THE VERTICAL STATION MARKED AS “A”, “B” AND “C” SHOWN IN FIGURE 9-17 FOR SUBPLOTS (A), (B) AND (C), RESPECTIVELY.....	247
FIGURE 9-19 – AVERAGE VELOCITY AS A FUNCTION OF Y_{FS} FOR THE VERTICAL STATION MARKED “D” IN FIGURE 9-17.	248
FIGURE 9-20 – MEDIUM RESOLUTION GRID, HIGH SPEED OBLIQUE COMPARISON WITH EXPERIMENTAL PHOTOGRAPHS OF THE FREE SURFACE IN THE NEAR WAKE OF THE CYLINDER	249
FIGURE 9-21 – MEDIUM RESOLUTION GRID, HIGH SPEED SIDE VIEW COMPARISON WITH EXPERIMENTAL PHOTOGRAPHS OF THE FREE SURFACE IN THE NEAR WAKE OF THE CYLINDER	250
FIGURE 9-22 – OBLIQUE COMPARISON OF THE FREE SURFACE CLOSE TO THE CYLINDER FROM THE PRESENT PARTIAL DEPTH SIMULATION TO THE EXPERIMENTS OF HAY (1947).	251
FIGURE 9-23 – SIDE VIEW COMPARISON OF THE FREE SURFACE CLOSE TO THE CYLINDER FROM THE PRESENT PARTIAL DEPTH SIMULATION TO THE EXPERIMENTS OF HAY (1947).	223
FIGURE 10-1 – SKETCH OF THE KEY LENGTHS MEASURED BY HAY (1947).....	253
FIGURE 10-2 – BOW WAVE HEIGHT AS A FUNCTION OF FROUDE NUMBER FROM ALL THE MEASUREMENTS OF HAY (1947).....	255
FIGURE 10-3 – PLOT OF THE D_1 AS A FUNCTION OF Fr_D FOR THE PRESENT WORK, HAY (1947) AND WIKRAMASINGHE AND WILKINSON (1997)	256
FIGURE 10-4 – PLOT OF L_0/L AS A FUNCTION OF Fr_L , FROM HAY’S (1947) FIGURE 92.....	257
FIGURE 10-5 – PLOT OF THE DEPTH OF THE VENTILATED CAVITY AS A FUNCTION OF Fr_D	258
FIGURE 10-6 – PLOT OF THE HEIGHT OF THE ROOSTER TAIL AS A FUNCTION OF Fr_D	259
FIGURE 10-7 – EXAMPLE OF THE SCALED MEASUREMENTS MADE FROM HAY’S IMAGES.	260
FIGURE 10-8 – PLOT OF THE LENGTH TO THE PEAK OF THE ROOSTER TAIL, L_3 FOR $D=50$ MM.	261
FIGURE 10-9 – POWER SPECTRAL DENSITY PLOTS FOR THE $Re_D = 54 \times 10^3$ SIMULATION.	263
FIGURE 10-10 – STROUHAL NUMBERS FROM THE PRESENT SIMULATIONS COMPARED WITH RESULTS FROM TWO META-ANALYSES OF SINGLE-PHASE EXPERIMENTAL STUDIES.	264
FIGURE 10-11 – COMPARISON OF COMPUTATIONAL RUN TIMES FOR THE 2 ND ORDER MODEL WITH ALTERNATE TURBULENCE MODELS.	266

FIGURE 11-1 – DRAG COEFFICIENTS AS A FUNCTION OF TIME FOR THE SIMULATIONS AT $Re_D=27\times 10^3$ AND $Re_D=54\times 10^3$	268
FIGURE 11-2 – COMPARISON OF THE DRAG COEFFICIENTS FROM THE PRESENT SIMULATIONS, WITH MAGNIFICATION OF THE PRESENT RESULTS, AND THE TWO INCH MEASUREMENTS WITH DIFFERENT DRAFTS FROM HAY (1947).	269
FIGURE 11-3 – COMPARISON OF THE TWO-PHASE DRAG COEFFICIENTS FROM THE PRESENT WORK AND HAY (1947) WITH THAT OF A SINGLE-PHASE CIRCULAR CYLINDER.	270
FIGURE 11-4 – SECTIONAL DRAG COEFFICIENTS FROM CHAPLIN AND TEIGEN (2003).	273
FIGURE 11-5 – C_D VALUES COMPUTED BY CHAPLIN AND TEIGEN (2003) WITH ADDITIONAL DATA REPRODUCED FROM ZDRAVKOVICH (1997).	274
FIGURE 11-6 – C_{FS} AS A FUNCTION OF Fr , REPRODUCED FROM (CHAPLIN AND TEIGEN, 2003).	275
FIGURE 11-7 – AVERAGE PRESSURE DISTRIBUTION ON THE FACE OF A, NOMINALLY, TWO-DIMENSIONAL CYLINDER FROM A THREE-DIMENSIONAL SIMULATION.	277
FIGURE 11-8 – AVERAGE PRESSURE DISTRIBUTION ON THE FACE OF A THREE-DIMENSIONAL CYLINDER WITH A FREE SURFACE, WHICH IS MARKED WITH THE SOLID LINE. NOTE THAT THE STILL WATER LEVEL IS AT $y=0.2m$ IN THIS PLOT.	278
FIGURE 11-9 – REPRODUCTION OF FIGURE 11-4 TRANSPOSED INTO THE PRESENT VERTICAL COORDINATES WITH THE SECTIONAL DRAG FROM THE PRESENT WORK INCLUDED.	279
FIGURE 11-10 – RECOMPUTED VALUES OF C_{FS} FROM HAY (1947), CHAPLIN AND TEIGEN (2003) AND THE PRESENT WORK.	281
FIGURE 12-1 – COMPARISON OF THE ELEVATION OF THE FREE SURFACE USING NO SURFACE RECONSTRUCTION AND THE PLIC METHOD, (A) AND (B) RESPECTIVELY.	290

List of Tables

TABLE 1-1 – EXAMPLE OF THE LIMITATIONS OF SIMULTANEOUSLY SCALING BOTH RE AND FR.....	4
TABLE 1-2 – MAJOR TYPES OF CHEMICAL AND BIOLOGICAL POLLUTANTS IN SEWAGE AND STORMWATER AND THEIR PRINCIPLE SOURCES, FROM WONG (2005) AND SHON ET AL (2006).	8
TABLE 1-3 – CYLINDER DEPTH AND DIAMETERS INVESTIGATED BY HAY.	21
TABLE 5-1 – EDGE DETAILS FOR THE SPANWISE PERIODIC MESHES WITH DIST = DISTRIBUTION TYPE; HT = HYPERBOLIC TANGENT DISTRIBUTION; U = UNIFORM NODE DISTRIBUTION.....	92
TABLE 5-2 – EDGE DETAILS FOR THE WATER TUNNEL MESH.	93
TABLE 5-3 – LIST OF THE LOCATIONS OF THE SPANWISE LINE PROBES.....	110
TABLE 6-1 – DETAILS OF THE AVERAGING STAGES FROM THE PRESENT WORK.	128
TABLE 6-2 – POWER LAW SLOPE CALCULATED VIA A LINEAR REGRESSION OF THE POINT PROBE DISCUSSED IN §6.4.3. THE FREQUENCY RANGE WAS FOR 4195 POINTS OVER 150-300HZ.....	156
TABLE 7-1 – KEY PARAMETERS OF THE BENCHMARK RIGHT CIRCULAR CYLINDER STUDIES TO BE USED TO VALIDATE THE PRESENT WORK.	174
TABLE 8-1 – EDGE NODE COUNT AND SPACING FOR THE EDGES SKETCHED IN FIGURE 8-1.....	186
TABLE 8-2 – EDGE LIST AND NODE COUNT FOR EDGES THAT ARE COMMON FOR ALL THE MODELS, WITH NODES SPACED UNIFORMLY (UNLESS NOTED OTHERWISE) ACROSS ALL THE LISTED EDGES.	199
TABLE 8-3 – LENGTH AND NUMBER OF THE NODES FOR THE VARIABLE LENGTH EDGE EF SHOWN IN FIGURE 8-14 FOR THE LENGTH TO THE OUTLET BOUNDARY TESTS.	201
TABLE 9-1 – MATRIX OF MESHES CONSTRUCTED PER CONFIGURATION OF CYLINDER DEPTH.	227
TABLE 9-2 – EDGE DETAILS FOR THE FULL DEPTH CYLINDER CONFIGURATION. DIST = DISTRIBUTION TYPE; HT = HYPERBOLIC TANGENT DISTRIBUTION; U = UNIFORM DISTRIBUTION.....	229
TABLE 9-3 – EDGE DETAILS FOR THE CUT OFF CYLINDER CONFIGURATION. DIST = DISTRIBUTION TYPE; HT = HYPERBOLIC TANGENT DISTRIBUTION; U = UNIFORM DISTRIBUTION.	231
TABLE 9-4 – TOTAL CELL COUNT FOR THE THREE GRIDS.	232
TABLE 9-5 – TIME STEP SIZE FOR THE DIFFERENT RESOLUTION AND SPEED COMBINATIONS.	234

List of Appendices

APPENDIX A : DETAILS OF THE NUMERICAL CONVERGENCE PROCEDURE WITHIN CFD-ACE+.....	319
A.1. INTRODUCTION	319
A.2. HOW THE RESIDUALS ARE COMPUTED WITHIN CFD-ACE+	319
A.3. USER SPECIFIED CONTROL OF RESIDUAL LIMITS AND THE ITERATIVE CYCLE	320
A.4. AN EXAMPLE OF ITERATIVE CONVERGENCE CONTROL	321
A.5. NOTES AND OBSERVATIONS ON CONVERGENCE.....	323
APPENDIX B : HYPERBOLIC TANGENT STRETCHING FUNCTION	325
B.1. DERIVATION	325
B.2. SAMPLE MATLAB CODE TO COMPUTE THE NODAL COORDINATES	326
APPENDIX C : SQUARE CYLINDER TWO-DIMENSIONAL TESTS	329
C.1. INTRODUCTION	329
C.2. COMMON CONFIGURATION FOR ALL THE PARAMETER STUDIES.....	330
C.2.1. Geometry and Mesh.....	330
C.2.2. Initial and Boundary Conditions	333
C.2.3. Solver Parameters.....	334
C.3. THE EFFECT OF VARYING THE LENGTH TO THE OUTLET BOUNDARY, \mathcal{L}	335
C.3.1. Alterations to the Common Configuration for the \mathcal{L} Tests.....	335
C.3.2. Convergence of the Solver During the Simulations.....	336
C.3.3. Examination of the Instantaneous Flow Field	336
C.3.4. Examination of the Lift and Drag Coefficients as a Function of Time	340
C.3.5. Statistical Characteristics of the Force Coefficients	348
C.4. INVESTIGATION OF THE EFFECT OF VARYING THE WALL NORMAL LENGTH OF THE FIRST CELL ADJACENT TO THE CYLINDER, \mathfrak{F}	351
C.4.1. Alterations to the Common Configuration for the \mathfrak{F} Tests.....	351
C.4.2. Convergence of the Solver during the Simulations.....	354
C.4.3. Examination of the Instantaneous Flow Field	355
C.4.4. Examination of the Lift and Drag Coefficients as a Function of Time	358
C.4.5. Statistical Characteristics of the Force Coefficients	365

C.5. SUMMARY AND RECOMMENDATIONS FOR THE THREE-DIMENSIONAL MESHES	367
APPENDIX D : SOURCE CODE.....	369
D.1. MAKEFILE	369
D.2. FLAG_PARAMETERS.F90	370
D.3. DYNAMIC_AVERAGE.F90	370
D.4. LIBUSERACE.F.....	377
APPENDIX E ADDITIONAL MEASUREMENTS FROM THE EXPERIMENTAL DATA OF HAY (1947).....	389
E.1. INTRODUCTION AND EXPERIMENTAL METHODOLOGY	389
E.2. ADDITIONAL WAVE HEIGHT MEASUREMENTS	391

Nomenclature

English Symbols

Symbol	Definition
A	area
a	finite volume equation general coefficient variable
b, B	bottom face/cell
C_s	Smagorinsky constant
$C_{\varepsilon 1}, C_{\varepsilon 2}, C_{\mu}$	closure constants for the $k - \varepsilon$ RANS model
c_{surf}	surface coefficient for VOF surface reconstruction
c_i and c_{μ}	constants of proportionality for the viscous and inertial “effects”
d	circular cylinder diameter, square cylinder side length
e, E	east cell face/cell
E_k	kinetic energy
$E(\kappa)$	energy as a function of wave number
F_E	ensemble average of a general function
f_i	inertial effects
f	general function
F_p	force due to pressure
F_{st}	surface tension forces
F_T	time average of a general function
F	volume fraction with VOF
F_{ϑ}	volumetric, spatial, average of a general function
f_{μ}	viscous effects
F_s	wall shear stress

G	filter function
\mathbf{g}	gravitation vector
H	channel height
h	depth from a reference point, for example when computing hydrostatic pressures
$I_{\tilde{\theta}}$	general time integral for a variable $\tilde{\theta}$
k	turbulent kinetic energy
l	integral length
l_c	characteristic length
m	mass
n/N	north cell face/cell
N	cell count, number of experimental repetitions
\mathbf{n}	surface normal vector
P	a general point when discussing the finite volume method
p	thermodynamic pressure
p_h	hydrostatic pressure
$S_{\tilde{\theta}}$	source term for variable $\tilde{\theta}$
s/S	south cell face/cell
S_{ij}	resolved strain rate tensor with LES
s_{ij}	strain rate tensor with RANS
\bar{S}	volume averaged source term
t	time (s); top cell face
T	time, when used in the temporal RANS average, or the top cell in the finite volume method
t_{ij}	viscous stress tensor with RANS models

U_i	average velocity in the i th direction
u_c	characteristic velocity
\hat{u}_i	filtered velocity with each hat representing one filtering iteration
u'_i	fluctuating velocity in the i th direction
u_i	instantaneous total velocity in the i th direction
u^+	non-dimensional wall velocity, $u^+ \triangleq \frac{U}{u_\tau}$
u, v, w	principle velocity components in a Cartesian reference frame
u_τ	wall velocity, $u_\tau \triangleq \sqrt{\frac{\tau_w}{\rho}}$
\mathbf{u}	velocity vector (m/s)
U_∞	free stream velocity
w/W	west cell face/cell
x_i	i th coordinate direction
\mathbf{x}	spatial coordinate vector
x, y, z	principle Cartesian coordinate axes
y^+	non-dimensional wall distance, $y^+ \triangleq \frac{u_\tau y}{\nu}$

Greek Symbols

Symbol	Definition
$\sigma_k, \sigma_\varepsilon$	closure constants for the $k - \varepsilon$ RANS model
θ	wall contact angel with VOF
ρ	density
Γ	diffusion coefficient when discussing the finite volume method
ε	dissipation rate
μ	dynamic viscosity

τ_{ij}	fluid stress tensor for a general fluid; specific Reynolds stress tensor with RANS
α	$\frac{1}{\text{Re}}$
$\nu = \frac{\mu}{\rho}$	kinematic viscosity
η	Kolmogorov length
τ	Kolmogorov time scale
v	Kolmogorov velocity scale
Δ	LES filter width
ξ	point distance vector when filtering for LES
σ	surface tension coefficient
ν_T	turbulent viscosity
λ	wave length
κ	wave number
τ_w	wall shear stress
ϑ	volume
δ	a small increment of a variable, for example δx
ϕ, ψ, ξ	general variables used for the explanation of RANS correlations

Mathematical Operators

$\nabla \times$	curl operator
$\nabla \cdot$	divergence operator
∇	gradient operator
$\frac{D}{Dt}$	substantive derivative
$\mathbb{N}(u_i)$	Navier-Stokes operator with RANS

Δt	a small time increment
Δx	a small spatial increment
O	order operator

Subscripts

Symbol	Definition
i, j, k	directional indices
w	wall

Superscripts

Symbol	Definition
o	indicates a variable at the current time step
$^+$	non-dimensional quantity
UP	variable computed from a first order upwind scheme
2UP	variable computed from a second order upwind scheme

Other Operators and Variables

Symbol	Definition
$\bar{\phi}$	general scalar when discussing the finite volume method
\mathcal{X}	blending factor for finite volume time integration
\mathcal{G}	blending factor for the finite difference schemes between a first order upwind method and a higher degree scheme
\mathcal{R}	geometric blending factor for central difference schemes
\mathcal{L}	length from the centre of the cylinder to the outlet boundary
\mathfrak{f}	wall normal cell length.
\mathcal{D}	two-dimensional distance of a point from a line

Non-dimensional Groups

Symbol	Definition
$Re \triangleq \frac{u_c l_c}{\nu}$	Reynolds number based on a characteristic velocity and length
Re_τ	turbulent Reynolds number
Re_H	Reynolds number based on the channel height
$We \triangleq \frac{\rho u_c^2 l_c}{\sigma}$	Weber number for describing surface tension

Acronyms

Acronym	Definition
2D	Two Dimensions
2OU	2 nd Order Upwind
3D	Three Dimensions
CFD	Computational Fluid Dynamics
CFL	Courant-Freidrichs-Lewy
CPU	Central Processing Unit
DCP	Development Control Plans
DES	Detached Eddy Simulation
DFT	Digital Fourier Transform
DLES2	2nd Conference on Dynamic and Large Eddy Simulation
DNS	Direct Numerical Simulation
FS	Free Surface
GPT	Gross Pollutant Traps
HEC-RAS	Hydraulic Engineering Corp – River Analysis System
HR	High Resolution
HS	High Speed

ILES	Implicit Large Eddy Simulation
L&R	Abbreviation of papers by D Lynn and W Rodi (Lyn and Rodi, 1994, Lyn et al., 1995)
LDA	Laser Doppler Anemometry
LEP	Local Environment Plans
LES	Large Eddy Simulation
LES Dyn	Dynamic Large Eddy Simulation model
LES LD	Locally Dynamics Large Eddy Simulation model
LR	Low Resolution
LS	Low Speed
MAC	Marker And Cell
MILES	Monotonically Integrated Large Eddy Simulation
MR	Medium Resolution
PIV	Particle Image Velocimetry
PLIC	Piecewise Linear interface Construction
POTEO	Protection of the Environment Operations
PSD	Power Spectral Density
RAM	Random Access Memory
RANS	Reynolds Averaged Navier-Stokes
RMS	Root Mean Squared
SF	Single Fluid
SGS	Sub-Grid Scale
SIMPLEC	Semi-Implicit Method for Pressure Linked Equations - Corrected
SLIC	Single Linear Interface Construction
SMAG	Smagorinsky

SPH	Smoothed Particle Hydrodynamics
UNSW	University of New South Wales
UTS	University of Technology Sydney
VOF	Volume of Fluid
WT	Water Tunnel geometric configuration

Abstract

The work presented in this dissertation is essentially a thesis in three distinct parts (single fluid validation, two fluid validation and data analysis) rather than the established approach for the development of a novel computational fluid dynamics solver. First, the progression is a traditional one, in which an existing technique was applied to a new area and subsequently extended. Second, from detailed analysis of the large volume of data generated in the validation process, a number of insights were gained into the flow features of the prototypes investigated that extended beyond a traditional validation study and discovered a number of new physical phenomena.

Previous researchers have used monotonically integrated large eddy simulation (MILES) methods to investigate a range of flows including turbulent decay in rotary valve engines and rocket body dynamics. MLES methods have the distinct advantage over standard LES simulation techniques in that they promise to provide similar levels of detail and accuracy but at a fraction of the computational cost. However, to the author's knowledge these techniques have not been applied to the prototype problem of this thesis: cylinders in cross flow without and with free surfaces. Hence the *raison d'être* of this thesis: to apply a faster yet equally accurate CFD method to a free surface problem via a validated single fluid investigation. Specifically, the progression was to first validate the method against a single right square cylinder in cross flow without a free surface and then to extend the method to a right circular cylinder in cross flow with a free surface.

With the right square cylinder without free surface the research focussed on the extensively studied configuration of a two dimensional square cylinder at a Reynolds number of 22×10^3 . Despite the agreement of the validation parameters with published data, detailed examination of the flow field revealed inconsistencies in the modelled results. In particular the power spectrum decay of the data appear too "easy" to obtain, indicating possible flaws in the theoretical basis, while correlation data apparently supports a conclusion that the previous assumption of four diameters domain width is too narrow to provide an uncorrelated flow region.

The free surface physics of the circular cylinder model was captured with the volume of fluid method and was applied to Reynolds number flows based on cylinder diameter of between 27×10^3 and 54×10^3 . These flows, at the provided grid resolution, push the

lower boundary of what can be called MILES, yet interpretations of the results indicates that the model is accurately capturing the physics of the flows.